BELLCOMM, INC.

SUBJECT: Meteoroid Hazard for Planetary Missions - Case 103-2

DATE: July 25, 1966

FROM: J. S. Dohnanyi

ABSTRACT

A model meteoroid environment for a Mars flyby mission is identified and the main considerations underlying the model discussed. The cometary meteoroid environment at 2 AU from the sun is found to be similar to the one near Earth; extrapolation from catalogued asteroids implies a flux that may be 4 or 5 orders of magnitude higher in the asteroid belt. Model impact velocities for both kinds of particles are estimated and the resulting penetration environment indicated. Plausible ways to measure directly the environment from space probes are discussed. An Explorer-type satellite is found to be useful in defining the environment to a much higher level of confidence than is now possible.

(NASA-CR-152880) METEOROID HAZARD FOR PLANETARY MISSIONS (Bellcomm, Inc.) 16 p

N79-73375

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MEMORANDUM FOR FILE

1. INTRODUCTION

During a manned Mars flyby mission the meteoroid environment is expected to differ from existing models (based on near-Earth data) for two reasons: (1) cometary meteoroids may not have the same flux at a distance of 2 AU from the sun as near Earth; (2) asteroidal debris may increase the meteoroid flux considerably at distances from the sun larger than 2 AU. This paper is a discussion of these two sources of hazards; a plausible way to reduce existing uncertainties by direct satellite measurements is indicated.

It is found that the near-Earth cometary meteoroid environment is similar to the one at about 2 AU from the sun, to a first approximation. A model environment for the asteroidal belt is defined. As a means of checking the environment, an Explorer-type mission is found to provide a useful "first cut."

2. SIGNIFICANT FLUX

This is the flux against which a spacecraft must be designed in order to meet a given mission success probability. The meteoroid giving rise to the significant flux is the design particle.*

For a spacecraft surface area of 140 meter^2, mission duration of 5.88×10^7 seconds (680 days) and reliability of 99 percent, the significant flux is

$$(2.1) \qquad N(m) = 1.22 \times 10^{-12} \text{ meters}^{-2} \text{ sec}^{-1}$$

where N(m) is the cumulative flux of particles having a given mass (in Kg) or larger.

*Since the particle flux is inversely proportional to some power of the particle mass, satisfactory protection against the design particle will surely be adequate against the more numerous smaller particles.

Within the asteroid belt, as will be discussed later, a more severe environment (i.e., the design particle has a larger mass) is expected. The length of time spent in this zone is about 2.07×10^7 sec (240 days). At 99 percent reliability, the significant flux in the asteroid belt for the same spacecraft becomes

$$(2.2) \qquad N(m) = 3.45 \times 10^{-12} \text{ meters}^{-2} \text{ sec}^{-1}$$

where the same notation has been used.

3. COMETARY METEOROIDS

In this section the design mass of cometary meteoroids is discussed. These particles are believed to originate from comets, are members of the solar system and their orbits are randomly distributed.

The significant flux for the whole mission, Eq. 2.1, corresponds to photographic meteors (near Earth) and is believed to be due entirely to cometary meteoroids (Jacchia et al, 1965). The flux vs mass relation for these meteors* is (Dohnanyi, 1966)**

$$(3.1) \qquad N(m) = 8 \times 10^{-18} \, m^{-1}, \qquad 10^{-2} > m > 10^{-5}$$

where N(m) is the cumulative flux of particles entering the Earth's atmosphere (per square meters per sec) having a mass of m (Kg) or larger.

In order to estimate the spatial variation, if any, of the cometary meteoroid flux, we consider Fig. 1 which is the distribution of photographic meteors in semi-major axis, a (in AU), and eccentricity, e, as given by McCrosky and Posen (1961). Circles are proportional to the number of meteors in a given range of a and e. The continuous curves are the values of a and e for which the perihelia q and aphelia q' have a value equal to the orbital radius of the planets indicated; the circular orbit at 2.8 AU from the sun corresponding to the "missing planet" inside the asteroidal belt is included. Since points on this plot falling outside a given doublet of curves (for a given planet) correspond to orbits with perihelia too short or aphelia too long to intersect the given planet's orbit, the doublet defines an effective "window" for the planet. Particles with a and e values outside this "window" do not intersect the planet's orbit and hence are never "seen" by it.

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*Reduced by McCrosky and Posen (1961).

**See Fig. 3, for a plot.

It can be seen, from the figure, that almost all meteors seen by Earth are also seen by Mars, and vice versa. The apparent increase in the number of meteors in the region overlapping the "window" of the Earth and that of Bode's "missing planet" may be spurious; they correspond to fast meteors which are more easily detected photographically than are slow ones.

One may therefore conclude that the cometary meteoroid environment near Mars is similar to the one near Earth and is given by Eq. 3-1, in a first approximation. The design particle then has a mass of 7×10^{-6} Kg.

The average Earth entry velocity of photographic meteors is 20 Km/sec (Dohnanyi, 1966) a value which includes the acceleration due to the Earth's gravity. When the latter is subtracted out, an average velocity of 17 Km/sec relative to the Earth is obtained. The spatial variation of this number requires further study.

4. ASTEROIDAL METEORS

A. Near-Earth Environment

In this section, the distribution of near-Earth asteroidal debris is discussed. While practically all meteors (near Earth) with a mass of the order of 10^{-3} Kg (1 gram) or smaller are believed to be cometary, large meteorites which survive entry into the Earth's atmosphere are generally believed to be asteroidal fragments.

Hawkins (1963) has estimated the near-Earth cumulative flux of stone and iron meteorites. His result is*

(4-A-1) stones: $\log N = -17.22 - \log m$

irons: $\log N = -19.10 - .7 \log m$

where MKS units are used throughout.

4. B. Deep Space Asteroidal Meteoroids

In this section, the meteoroid environment in the asteroidal belt is discussed.

In the absence of direct information, extrapolation from the distribution of telescopically observed asteroids is necessary. This means an extrapolation of over 15 orders of

*For a plot, see Fig. 3.

magnitude in mass, with correspondingly larger uncertainties in the results. To convert mass distributions into flux distributions, however, the average particle velocity relative to the spacecraft must be defined.

All catalogued asteroids have, with few exceptions, orbits within the asteroidal belt (2 to 3.5 AU from the sun) with average inclination (to the ecliptic) of 10° and mean eccentricity of about .15. These distributions are sharply "peaked" and one can, therefore, define a particle relative velocity V_{rel} (with respect to the spacecraft). For a spacecraft orbit with a semi-major axis of 1.6 AU, one finds,

(4-B-1) $V_{rel} = 6 \pm 3$ Km/sec.

Combining this with the number distribution of asteroids (Kuiper et al, 1958), one finds*

(4-B-2) $1.6 \times 10^{-18}\, m^{-.63} < N(m) < 4.2 \times 10^{-13}\, m^{-1}$

where N(m) is the cumulative mass flux, in MKS units, relative to our spacecraft in the asteroidal belt.

This gives, for the design mass, m_d,

(4-B-3) 6×10^{-8} Kg $< m_d <$ .12 Kg.

NAA employs a model flux** of asteroidal meteoroids, based upon reference 8

(4-B-4) $N(m) = 2.5 \times 10^{-14}\, m^{-1}$ $\quad r \geq 2.1$ AU

$= 0$ $\quad r < 2.1$ AU

where r is the distance from the sun. Because of convenience, this model will be used for the purpose of calculating the nominal design flux.

5. PENETRATION CRITERIA

This section is a discussion of spacecraft protective shield thicknesses required for the mission. In the present range of impact velocities, 6 Km/sec to 17 Km/sec, the Ames (Summers, 1959) penetration criteria are adequate. Accordingly, the

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*See Fig. 3, for a plot.

**See Fig. 3, for a plot.

thicknesses of equivalent aluminum penetrated by the design particle (of each kind) are summarized* in Table 5-1.

TABLE 5.1

Thickness (in meters of Al equivalent) penetrated by the design particle for various bumper configurations

Bumper Effectiveness	Cometary	Asteroidal
Single sheet	7×10^{-3}	$1.1 \times 10^{-3} \longrightarrow .14$
x2	3.5×10^{-3}	$5.5 \times 10^{-4} \longrightarrow 7 \times 10^{-2}$
x5	1.4×10^{-3}	$2.2 \times 10^{-4} \longrightarrow 2.8 \times 10^{-2}$
x10	7×10^{-4}	$1.1 \times 10^{-4} \longrightarrow 1.4 \times 10^{-2}$
x20	3.5×10^{-4}	$5.5 \times 10^{-5} \longrightarrow 7 \times 10^{-3}$

For Cometary particles, an effectiveness of x20 can probably be achieved.** For asteroidal particles x5 is believed appropriate. Bumpers for low velocity projectiles are, of course, subject to empirical test.

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6. DEEP SPACE METEOROID SATELLITE

This section is a discussion of the type of direct measurements needed to establish the asteroidal meteoroid environment with reasonable confidence.

The NAA model flux Eq. 4-B-4 will be used as a standard for reference and with reasonable assumptions,*** the penetration environment can be defined. This is plotted in Fig. 2. The shaded area is the uncertainty determined from Eq. 4-B-2. Cometary fluxes are included for reference. The dashed horizontal

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*Average perpendicular impact velocity is taken as 1/2 times the velocity; the density of cometary and asteroidal meteoroids is taken to be 10^3 Kg/m^3 and 3.5×10^3 Kg/m^3, respectively. A "spallation factor" of 1.8 is assumed (Orrok, 1964).

**G. T. Orrok, private communication.

***A particle density of 3.5×10^3 Kg/m^3, velocity of 6 Km/sec and the Ames penetration criteria with a spall factor of 1.8 have been employed.

line is the significant flux in the asteroidal belt. Solid horizontal lines are satellite exposures, as indicated. Arrows define the number of punctures a given satellite exposure will collect at 50 percent confidence during a mission duration of 2.07×10^7 sec (240 days) at the indicated sensor thicknesses. Areas of 2.4 m^2 and 200 m^2 have been used for Explorer and Pegasus-type missions, respectively.

The 100 count points are interesting because in the event the asteroidal flux is lower than the cometary, the satellites will count about one cometary particle penetration at the respective single sheet thicknesses. Even more significant are the points for which the nominal expected number of counts is 1250; for these points one expects about 10 punctures by cometary particles. These points correspond to thicknesses of 2.5×10^{-4} meters and 1.3×10^{-3} meters of Al equivalent for Explorer and Pegasus satellites, respectively. For these thicknesses, one is "assured" of about 10 counts if the asteroidal environment turns out to be less "severe" than the cometary one. Since, however, these points correspond to flux levels 7 and 5 orders of magnitude (in Explorer and Pegasus missions, respectively) higher than the significant flux for the manned mission, information obtained from them is not as relevant as would be desirable.

As a useful compromise, the 100 count points may be flown in combination with sensors sufficiently thin ($\sim 10^{-4.4}$ meters = 1.5 mils) to measure very small particle penetrations, for calibration. A "first cut" at the environment may be obtained in this manner.

In Section 4-B of this paper, the strong directionality of asteroidal particles has been indicated. It therefore is important to include a check on the directionality of the flux of asteroidal particles in a deep space experiment.

7. DISCUSSION AND CONCLUSION

Summary chart Fig. 3 is a plot of the meteoroid environment discussed in the paper. The various measured and estimated fluxes are indicated. The uncertainty in the asteroidal meteoroid flux when extrapolated through about 15 orders of magnitude is evident. Details of the figure have been discussed in the text and will not be repeated here.

Due to the large uncertainty in the asteroid belt environment, satellite measurements are sorely needed. An Explorer-type satellite could furnish a useful "first cut" in defining the environment to a first approximation. Such a "refined" model would then be the basis for the design of more sophisticated experiments to check out the environment at a satisfactory level of confidence.

1011-JSD-skc

J. S. Dohnanyi

Attachments
Figures 1-3
References

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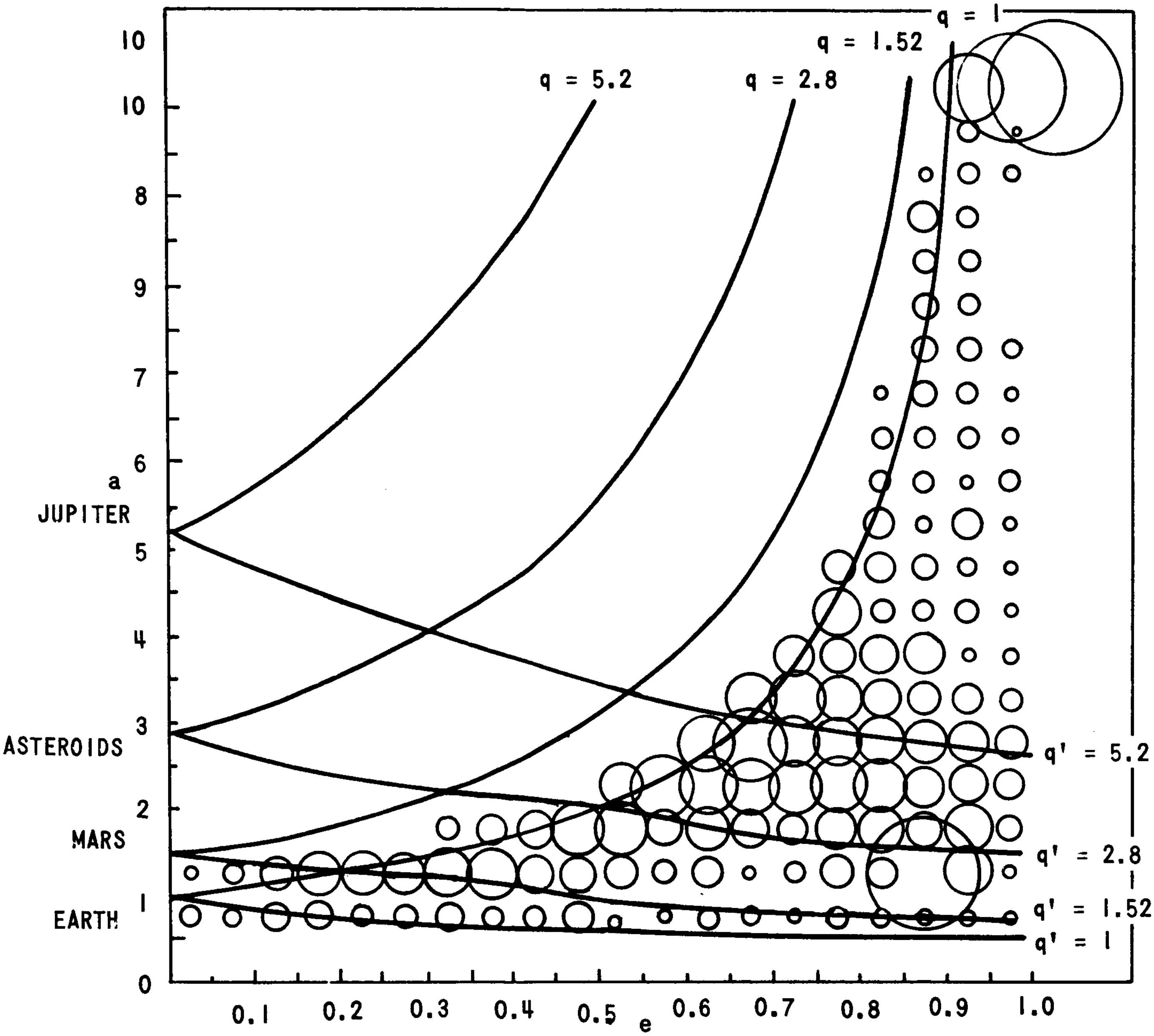
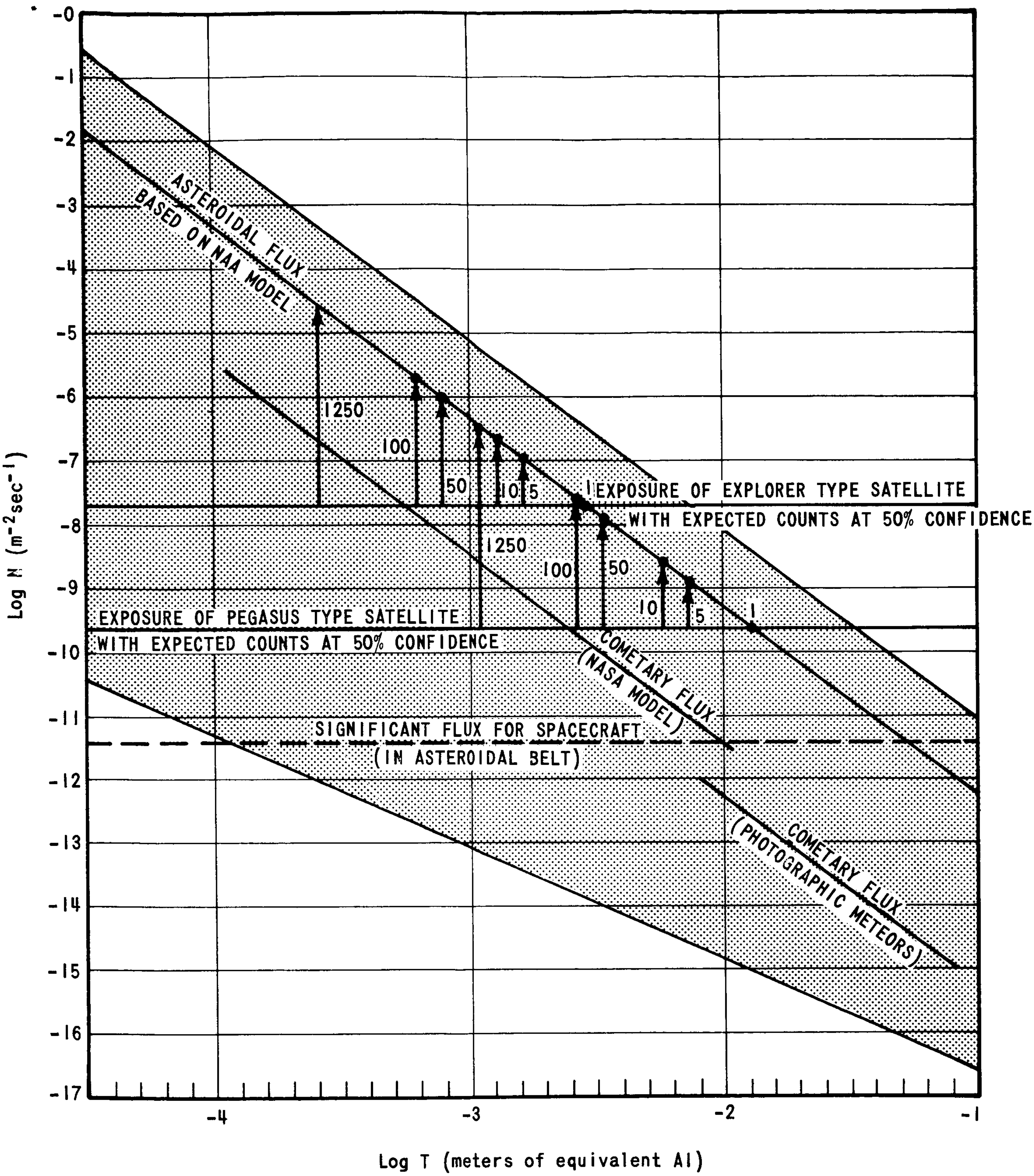
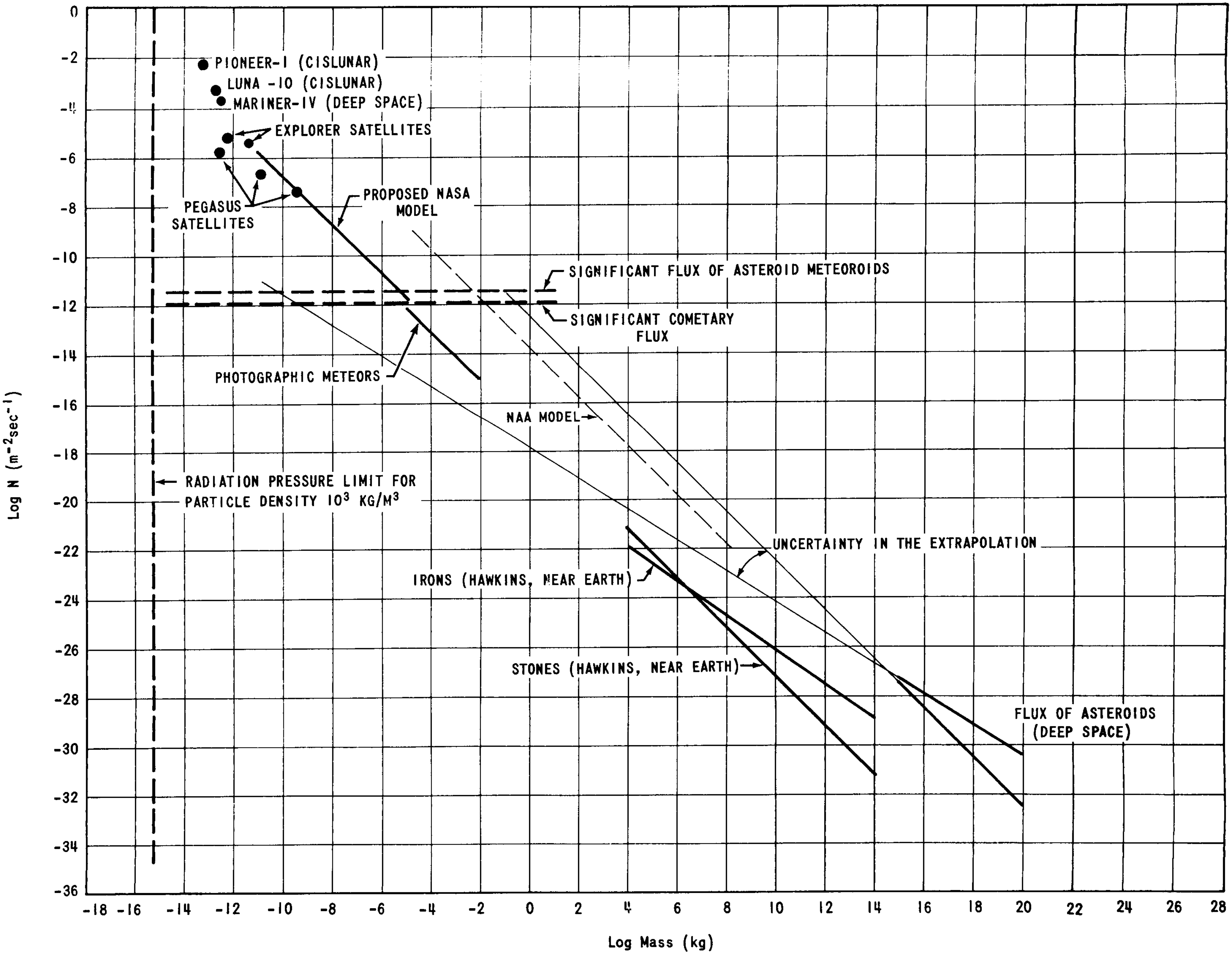


FIGURE I - DISTRIBUTION OF METEOR ORBITS IN ECCENTRICITY AND SEMI-MAJOR AXIS: OBSERVED NUMBERS, ALL ORBITS



-0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
Log N ($m^{-2}sec^{-1}$)
-4
-3
-2
-1
Log T (meters of equivalent Al)
ASTEROIDAL FLUX
BASED ON NAA MODEL
1250
100
50
10
5
1
EXPOSURE OF EXPLORER TYPE SATELLITE
WITH EXPECTED COUNTS AT 50% CONFIDENCE
1250
100
50
10
5
1
EXPOSURE OF PEGASUS TYPE SATELLITE
WITH EXPECTED COUNTS AT 50% CONFIDENCE
COMETARY FLUX
(NASA MODEL)
SIGNIFICANT FLUX FOR SPACECRAFT
(IN ASTEROIDAL BELT)
COMETARY FLUX
(PHOTOGRAPHIC METEORS)

FIGURE 2


PIONEER-I (CISLUNAR)
LUNA -10 (CISLUNAR)
MARINER-IV (DEEP SPACE)
EXPLORER SATELLITES
PEGASUS SATELLITES
PROPOSED NASA MODEL
SIGNIFICANT FLUX OF ASTEROID METEOROIDS
SIGNIFICANT COMETARY FLUX
PHOTOGRAPHIC METEORS
NAA MODEL
RADIATION PRESSURE LIMIT FOR PARTICLE DENSITY 10³ KG/M³
UNCERTAINTY IN THE EXTRAPOLATION
IRONS (HAWKINS, NEAR EARTH)
STONES (HAWKINS, NEAR EARTH)
FLUX OF ASTEROIDS (DEEP SPACE)
Log N (m⁻²sec⁻¹)
Log Mass (kg)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
-36
-18 -16 -14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20 22 24 26 28

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